FUTURE SPACE INFRARED MISSIONS IN JAPAN

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ABSTRACT

In Japan, the infrared astronomy satellite has been regarded as one of the most important mission types in the space science programs of Japan, since the success of the first infrared mission, IRTS. ASTRO-F is the second Japanese infrared satellite, it is an all-sky survey mission with a 67-cm telescope, and is to be launched in early 2004. For the next generation infrared satellite, we have proposed two different types of mission. One is the SPICA mission, a large (3.5 m), cooled (4.5 K) telescope for advanced observations in the mid- and far-infrared range, and it is proposed to be launched in 2010. Another is an out-of-ecliptic mission to measure the cosmic infrared background from the interplanetary space free from the zodiacal light/emission. The launch year is planned to be around 2015. These future infrared missions are outlined, and the technology development required for them is discussed.

INTRODUCTION

Since the success of the IRAS mission, infrared observations from space have been a powerful tool in many fields of astronomy. In 1995, the first Japanese infrared mission called IRTS (InfraRed Telescope in Space) was launched by HII rocket (owned by NASDA: National Aeronautics and Space Development Agency) as a part of the Space Flyer Unit (SFU). IRTS was a liquid-helium-cooled 15-cm telescope designed to study the diffuse infrared background in a wide wavelength range from near-infrared to far-infrared [1]. Spectroscopic measurements of zodiacal light/emission, interstellar emission bands, and the cosmic infrared background with much better spatial and spectral resolution than that of COBE were carried out during the mission life of three weeks. The wide-field spectroscopic survey by IRTS has greatly impacted the fields of interstellar matter studies and observational cosmology.

Following the IRTS mission, we started developing the second infrared telescope for detailed study of individual sources and for resolving the background radiation seen by the IRTS. This mission formerly called IRIS, now called ASTRO-F [2], was designed to be the largest cooled telescope (~1m class) ever to be previously launched. However, SIRTF and ISO, both observatory-type missions, with similar size telescopes, had already been planned before the mission study of ASTRO-F was complete. In pursuit of mission uniqueness and scientific merit, we decided to make ASTRO-F a survey-type mission. ASTRO-F will make an all-sky map in the far-IR and also perform deep-imaging and spectroscopic observations in a wide wavelength range from near-IR to far-IR. It is scheduled to launch in early 2004.

Since ASTRO-F will provide an all-sky survey and supposedly find many new objects, the next mission should be a space observatory with a large telescope for detailed study of the objects discovered by the ASTRO-F. SPICA [3] is such a mission, optimized for mid- and far-IR observations, and it is complimentary to the other large telescope missions planned by other countries, i.e. Herschel Space Observatory (HSO) for the sub-mm range and NGST for the near- and mid-IR. The initial mission study for SPICA has already been done, and the mission will be scheduled in the near future.

It has recently been reported that the near- and far-infrared background brightness measured by COBE and IRTS is too high (by a factor >2) to be explained by the integrated light of faint galaxies. This result impacts the standard evolutionary scenario of galaxies and forces us to search for the energy source powering the background excess. SPICA and the other future large telescope missions could be sensitive enough as to resolve the extragalactic background into individual galaxies. However, if the background is composed of diffuse gas or extended sources, the mystery of the background excess could be solved only by further measurement of the background. Moreover, even though large telescopes (like SPICA and

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NGST) are extremely sensitive, their sensitivity in the mid-infrared would be limited by the zodiacal background noise. Hence we propose an out-of-ecliptic mission, which enables extragalactic background measurements free from contribution of the zodiacal background.

This paper describes the current plan for future space infrared missions in Japan, introducing the above three different types of mission. The technology development required for these missions is also discussed.

FUTURE INFRARED MISSIONS

ASTRO-F

ASTRO-F is designed as the second-generation survey mission, following IRTS. ASTRO-F has a 67-cm telescope cooled to 5.8 K, and covers a wide wavelength range from K-band to 200 μm with two focal plane instruments; the Far-Infrared Surveyor (FIS) [4] and the InfraRed Camera (IRC) [5]. FIS will perform the all-sky survey with four photometric bands in the range of 50-200 μm using two-dimensional Ge:Ga photoconductor arrays. IRC will make the deep sky survey in selected sky regions in the near- and mid-infrared photometric bands with large-format focal plane arrays.

Figure 1 shows the real aspect of the ASTRO-F satellite, though it shows in fact the thermal test model. The liquid-helium cryostat is on top of the spacecraft. The total weight of the satellite is approximately 960 kg. Figure 2 shows the cross-sectional view of the cryostat. The outer shell is cooled to ~200 K by radiative cooling. The telescope and most of the focal plane instruments are cooled to 5.8 K by the helium vapor. The FIS instrument, which is connected to the helium tank, is cooled to ~1.8 K. One of the most distinctive technical features of the ASTRO-F cryostat is the adoption of cryo-coolers. Owing to the two-stage Stirling-Cycle coolers, which provide additional cooling power for the vapor-cooled shield, the hold time of liquid helium will be ~500 days, even with the small amount of liquid helium (170 liter) onboard. Even after the helium runs out, we can continue the near-infrared observations for the life of the coolers, ~5 years.

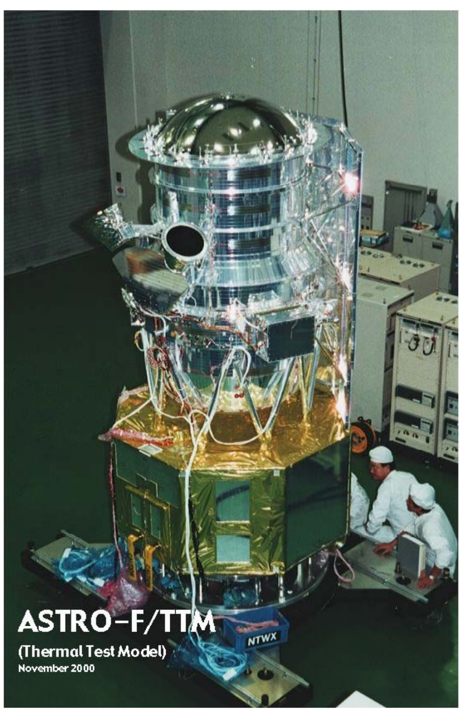

Figure 1: Thermal test model of the ASTRO-F.

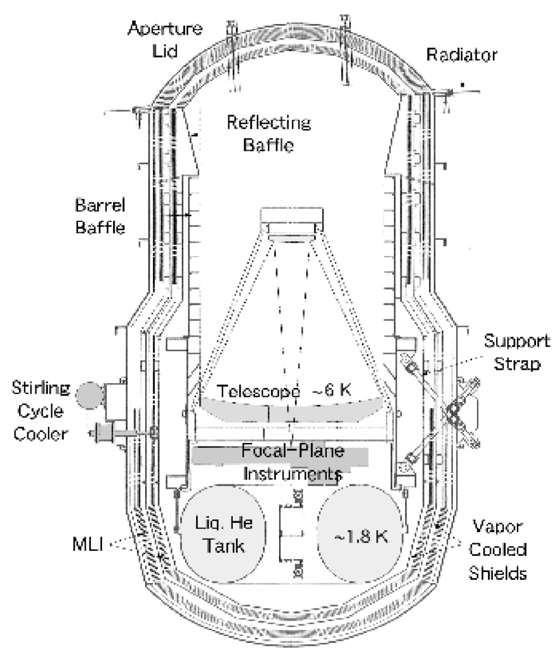

Figure 2: Cross-sectional view of the cryostat.

The telescope is a Ritchey-Chretien type, and silicon carbide (SiC) has been chosen for the mirror material because of its high strength and good thermal conductivity [6]. The mirror consists of a 3-mm thick porous SiC core with low area density (1.85 g/cm^3), and of a 0.5-mm thick, polished CVD surface layer. Due to this structure, the mirror weight is very low; the primary mirror weighs only 11 kg. The surface accuracy of the mirror after polishing is good enough to provide diffraction-limited image quality at 5 μm.
FIS is designed primarily to perform the all-sky survey in four photometric bands with the diffraction-limited spatial resolution as shown in Table 1. The detectors for the short wave bands are 2-D monolithic Ge:Ga arrays, which are directly connected to the cryogenic readout circuit by the Indium bump technology. For the long wave bands, compact stressed Ge:Ga arrays with stacked planar cavity structures are used. The current status of the development of the FIS detectors is described in the separate paper in this volume [7]. FIS also has spectroscopic capability as a Fourier-Transform Spectrometer (FTS) [8] with the highest resolution of 0.2 cm^{-1}. The FTS will be operated in pointing observation mode at polar regions in the ASTRO-F orbit, after FIS completes the all-sky survey. Owing to high performance of the detector arrays and to high spatial resolution, the point-source sensitivity of the FIS all-sky survey will be better than that of IRAS by more than one order of magnitude, and will reach to the confusion limit at a wavelength longer than 100 μm.

Table 1: *Specification of FIS*

Band	Wavelength [μm]	Pixel FOV [arcsec]	Array format
N60	50 – 75	30	20 x 2 Ge:Ga
WIDE-S	50 – 110	30	20 x 3 Ge:Ga
WIDE-L	110 – 200	50	Stressed 15 x 3 Ge:Ga
N170	150 – 200	50	Stressed 15 x 2 Ge:Ga

IRC is designed for deep imaging in the near- and mid-infrared wavelengths with wide FOV of 10’ x 10’ and will have nearly diffraction-limited spatial resolution, as shown in Table 2. Each channel has three photometric filter bands, and the filter wheel selects one of them. Owing to high-sensitivity large format arrays, the IRC will achieve the confusion- or background-limited point source sensitivity for the pointing mode observation. IRC also performs low-resolution ($\lambda/\Delta\lambda \sim 100$) spectroscopic observations with grism/prism optics mounted on the filter wheel.

Table 2: *Specification of IRC*

Channel	Wavelength [μm]	Pixel FOV [arcsec]	Array format
NIR	1.8 – 5	1.5	512 x 412 InSb
MIR-S	5 – 12	2.3	256 x 256 Si:As
MIR-L	12 – 26	2.3	256 x 256 Si:As

The specification of the ASTRO-F instruments is similar to that of SIRTF. The sensitivity of SIRTF is better than that of ASTRO-F because of the telescope size and the exposure time differences, but the all-sky survey and wide-field imaging observations by ASTRO-F should be complementary to the SIRTF deep survey and will be a valuable guide map for future large aperture space telescopes, e.g. HSO, NGST and SPICA. The ASTRO-F project is now in design fixing and system testing phase. The focal-plane instruments will be finalized by fall, 2002, and delivered to the cryostat for the refurbishment. The satellite will be launched in early 2004, after the final system tests covering two years.

SPICA

ASTRO-F will observe distant galaxies, but its telescope size is not large enough to resolve most faint galaxies at very high redshift. The sensitivity is, then, limited by the confusion noise. HSO and NGST will answer the requirement of large infrared telescope, but the sensitivity of these passively cooled telescopes is limited by the thermal emission from the telescope. On the other hand, SPICA is a new observatory-type mission with a large, cooled telescope optimized in the mid- and far-infrared. A conceptual view of the SPICA is shown in Figure 3, and its specifications are summarized in Table 3.

Table 3: *Current specifications of SPICA*

Parameter	Value
Mirror size	3.5 m in diameter
T_{mirror} in orbit	4.5 K
T_{mirror} at launch	300 K
Wavelength	5 – 200 μm (diffraction limit at 5 μm)
Orbit	S-E L2 Halo
Cooling	Radiative cooling + Mechanical coolers
Total mass	2,600 kg
Launch vehicle	H-IIA rocket
Launch year	2010

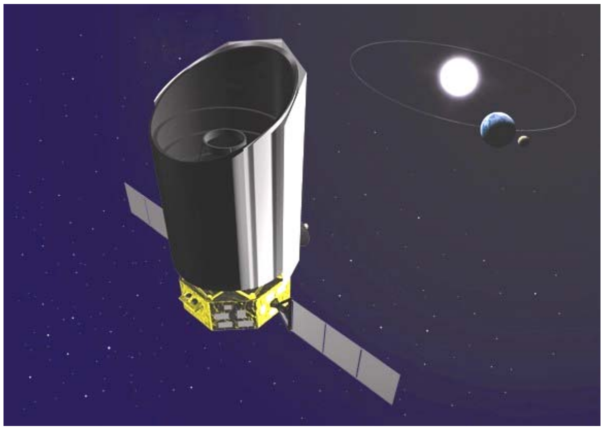

Table 3: *Current specifications of SPICA*

Former infrared satellites have carried their liquid helium cooled telescope and instruments into orbit in order to achieve high sensitivity in the mid- and far-infrared. Their cryostats were generally space-and mass-consuming, and their mission life limited by the hold time of liquid helium. For the SPICA mission we propose a warm-launch telescope that does not require room for the cryostat in the launch vehicle. Its telescope diameter, 3.5 m, is the maximum size available for the payload fairing of the H-IIA rocket.

The warm-launch concept can be realized by adopting an advanced cooling scheme with efficient radiative cooling and a compact mechanical cooler. Figure 4 shows the schematic diagram of the cryogenic system of SPICA.

The telescope is enshrouded with multi-layered radiators, which provide most of the cooling power to maintain the heat balance. In order to achieve effective radiative cooling, we chose a halo orbit around one of the Sun-Earth L2 point for SPICA. Since in this orbit the satellite stays always on the night side of the Earth, the radiation from both the Sun and the Earth can be easily shielded. In this configuration the telescope temperature of ~30 K is obtainable by the radiative cooling only.

The combination of a two-stage Stirling cycle cooler, as is used for the ASTRO-F, and a Joule-Thomson (JT) cooler with ^{4}He helps further cool the telescope. The cooling power required for the cooler is about 30 mW at 4.5 K, which is already achieved by the cooler [9] for SMILES on the international space station. To cool the far-infrared instruments, which require temperatures lower than 2 K, we plan to use another JT cooler with ^{3}He. A proto model of this system has already achieved the cooling power of 4 mW at 1.7 K.

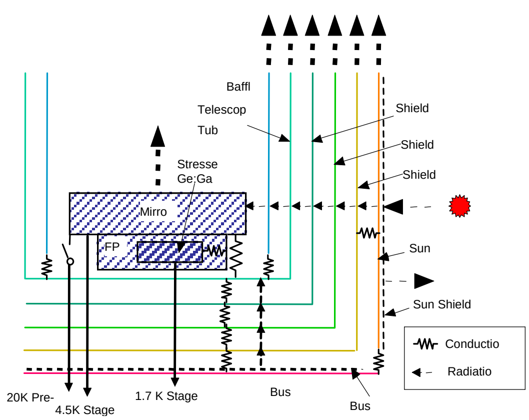

Figure 4: *Schematic view of the cryogenic system.*

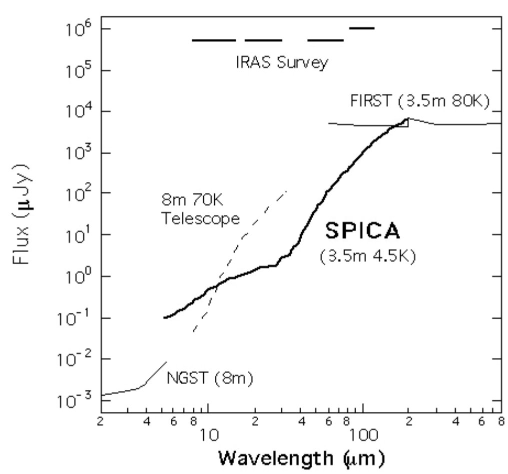

Figure 5: *Point-source sensitivity of SPICA (5σ, τ = 3,600s, $\lambda/\Delta\lambda$ =5).*

The focal plane instruments for SPICA are in their initial development phase. The core wavelength range is 5-200 μm, covered by a mid- and far-infrared camera/spectrometer. The camera performs deep imaging observations with the pixel FOV of the diffraction-limited image size and the total FOV of ~6', in all the wavelength bands. The spectrometer has modest resolution ($\lambda/\Delta\lambda \sim 10^3$) optimized for observations of distant objects. The coronographic observation mode for the direct detection of extra-solar planets is to be equipped. The focal plane arrays for ASTRO-F to some degree are proto-types for the SPICA detectors. However, more advanced photoconductor arrays and new generation devices with the NEP of $<10^{-18}$ W/rtHz are being explored: quantum well/dot, SIS photon detector, etc., are being developed. Various kinds of structure and material for the lightweight large telescope have been proposed, and the initial selection will be done in the near future.

Shown in Figure 5 is the photometric sensitivity of SPICA for point sources, limited by the natural background noise; the zodiacal background noise in the mid-infrared, and the confusion noise by the galactic cirrus and faint galaxies in the far-infrared. Since SPICA has an actively cooled telescope, its mid- and far-infrared sensitivity is superior to that of the other large, radiatively cooled, telescope missions.

Out-of-ecliptic mission

The observation of the extragalactic infrared background light gives an important clue into the cosmological evolution of galaxies and the high-z universe, because it contains the information on the total energy released from diffuse gas and very faint objects in the early universe, which cannot be resolved into individual sources even with very large telescopes. In fact, the near- and far-infrared backgrounds detected by COBE [9-11] and IRTS [12], shown in Figure 6, show a large discrepancy with the integrated flux of galaxies calculated from the deep galaxy survey and their extrapolation based on standard galaxy evolution models. Therefore, the total energy flux of the background cannot be explained by known galaxy populations that should contribute to the background. In the near-infrared, the fluctuation of the extragalactic background with a scale of ~1 degree was detected [12]. These results greatly impact the fields of galaxy evolution and cosmology.

The brightness of the extragalactic background shown in Figure 6 is obtained by careful subtraction of the zodiacal light and interplanetary dust emission by using intensity variations against the ecliptic coordinate and the zodiacal cloud model. At low ecliptic latitude where the zodiacal brightness is high, it can be precisely subtracted from the observed brightness. At high ecliptic latitude, however, estimation of the zodiacal brightness is quite uncertain because of its small ecliptic-latitude dependence. If the zodiacal background contains an isotropic component [13], it cannot be separated from the extragalactic background. The mid-infrared extragalactic background has never been positively detected, because the zodiacal background is so strong that the faint extragalactic component is easily affected by the temporal/spatial fluctuation of the zodiacal brightness and by the model uncertainty of the zodiacal dust cloud.

Hence, we propose an out-of-ecliptic mission, which measures the absolute flux of the infrared background precisely without uncertainty caused by contribution of the zodiacal background. One of the orbits appropriate for this type of mission is the heliocentric polar orbit with the Jupiter swing-by (Figure 7), which Ulysses, ESA's interplanetary space probe, has taken. The thick line in Figure 6 is the estimated

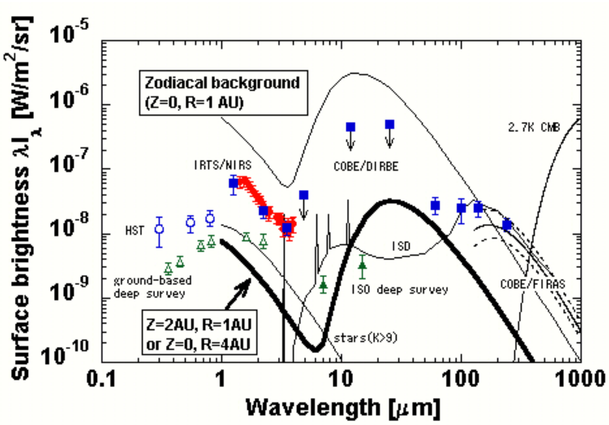

Figure 6: *Observations of extragalactic background.*

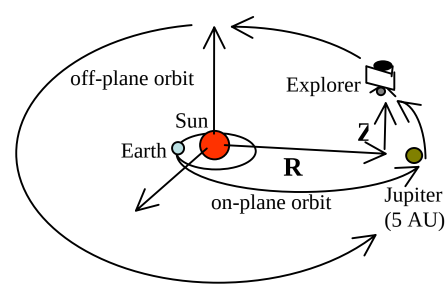

Figure 7: *The heliocentric polar orbit.*

zodiacal contribution at the off-plane height of Z = 2 AU and R = 1 AU or in the ecliptic plane but far from the sun (R =4 AU), according to a traditional zodiacal dust distribution model called fan-model. It almost reaches the levels of the integrated flux of known galaxies, and so the extragalactic background must be directly detected even in the mid-infrared wave bands.

The current specifications of this mission are shown in Table 4. According to currently available technology, it will take about 5 years to get to 5 AU. At 5 AU, the solar power is not high; therefore, the whole system should have a long life and low power consumption. The core wavelength range is where the zodiacal brightness dominates in the total sky brightness. The mid- and far-infrared detectors have to be cooled to <4 K to minimize the dark current, which causes the zero-point flux uncertainty. The cryogenic system which meets these requirements is the warm launch system with a combination of the radiative cooling and the cryo-coolers. In this orbit, the radiator enjoys full advantage of the location far from the Sun. The cryo-technology developed for the SPICA can be directly transferred for this mission.

Table 4: *Out-of-ecliptic mission spec*

Parameter	**Value**
Mirror size	~0.5 m
T_{mirror} in orbit	<10 K
T_{mirror} at launch	300 K
Wavelength	1 – 100 μm
Orbit	Heliocentric polar orbit (Jupiter swing-by)
Cooling	Radiative cooling + Mechanical coolers
Total mass	~500 kg
Launch vehicle	H-IIA rocket + additional propulsion
Launch year	< 2015

The total mass which the H-IIA rocket can carry to the heliocentric polar orbit is much smaller than the mass of SPICA in the S-E L2 orbit, because of the additional mass of substantial amounts of the propulsion to escape from the near earth orbit, a large solar panel, and a powerful communication antenna.

The focal plane instruments are wide-band, low- or medium-resolution spectrometers and imagers with relatively small format arrays in all the wave bands because of limited data-link capability, though the onboard data processing should help to reduce the data rate. Extremely low natural background condition will enable high sensitivity mid-infrared observations with ultra-wide-band instruments, e.g. FT-spectrometer. High sensitivity detectors for low-background use, especially in the 25-50 μm range, are obviously required. This mission would possibly be a precursor of a future out-of-ecliptic large telescope mission which can achieve the best sensitivity in the mid-infrared.

SUMMARY

In this paper, three different types of future infrared astronomy missions are introduced. Each of these missions has its own unique capability, but the new technology required for each of them can be commonly developed, because these missions are in a series where one is the natural extension to the next in both science and technology terms. It is worthy to note that the discussion on the next future missions, e.g. long-baseline interferometer or extremely large single dish, has already started.

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